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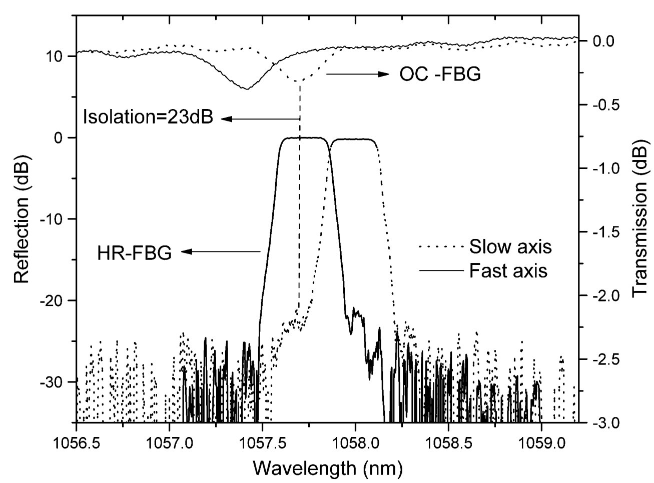

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Dual-Wavelength, Linearly Polarized All-Fiber Laser With High Extinction Ratio

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Abstract: We demonstrate a dual-wavelength linearly polarized all-fiber laser emitting 1-μm and 1.5-μm wavelengths with a total output power of 1.3 W. The laser consists of two pairs of fiber Bragg gratings (FBGs) fabricated on PM fibers to form a cavity and an Er/Yb co-doped fiber as a gain medium. A high extinction ratio of 23 dB is achieved using specially designed PM FBGs. The laser output has a narrow bandwidth of 26 pm at both 1057 and 1554 nm. When the dual-wavelength all-fiber laser is used to pump a PPLN crystal, the generation of mid-infrared emission at 3.3 μm is successfully demonstrated.

Index Terms: Fiber lasers, Fiber gratings.

1. Introduction

High power fiber lasers with linear-polarization output are essential for many applications, such as second harmonic generation (SHG), polarized laser beam combining, and interferometer sensing. However, developing such lasers with all-fiber structure, narrow linewidth and high polarization extinction ratio (PER) is a challenge. There are several designs reported to achieve linear-polarization output in recent years. Liu et al. reported a linearly-polarized fiber laser with a PER of 17–20 dB using tightly-coiled high-birefringence fiber [1]. Despite its success in achieving a high output power of 405 W, its 1.9-nm linewidth is too broad for SHG. Li et al. reported a high power fiber laser using a single-polarization fiber from Corning for polarization selection and achieved 17–20 dB of PER [2]. Nevertheless, the lasers reported in [1] and [2] used dichroic mirrors to separate pump and lasing wavelengths and bulk optics to couple the light in and out of the gain fiber. Therefore, they were not all-fiber designs. We tried to design an all-fiber laser using a single-polarization fiber for polarization selection and a fiber Bragg grating (FBG) for wavelength selection. A narrow linewidth of 0.054 nm and high PER of 28 dB at an output power of 1.7 W were obtained [3]. However, the shape mismatching between the elliptic core of the single-polarization fiber and the circular core of the gain fiber caused light to leak at the splicing point, thereby limiting the output power scale-up. Shirakawa et al. pioneered a new fiber laser design for linearly polarized output using two FBGs made on polarization maintaining (PM) fiber with the slow-axis wavelength of one FBG matching the fast-axis wavelength of the other FBG. The highly reflective (HR) FBG was spliced to the gain fiber with its axes aligned, while the output coupler (OC) FBG was cross-spliced to the gain fiber. In that design only one polarization was selected in the cavity [4]. The laser achieved 8 W of output power and 18 dB of PER. The main drawback of the laser was the requirement of a temperature controller to keep two wavelengths of FBGs aligned within the narrow bandwidth of the FBGs. We improved the PM FBG cavity design by fabricating a HR FBG with a top-flat, almost

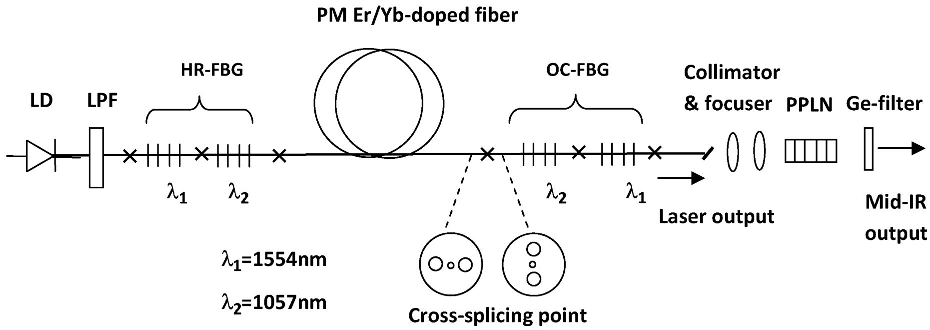

Fig. 1. A schematic diagram of the dual-wavelength linearly polarized Er/Yb co-doped fiber laser and mid-IR generation.

rectangular-shaped reflection spectrum. The wavelength of the OC FBG on the slow axis matched the HR FBG on the fast axis within 30 pm to ensure 20-dB isolation between two polarizations [5]. As a result, the laser achieved single-polarized output of 20 W, a linewidth of 0.22 nm, and a PER of 23 dB with no temperature controlling required. Very recently, we used a similar structure to scale up the power to 100 W at 1120 nm with a PER of 15 dB and a linewidth of 0.21 nm [6]. A further power scale up to 600 W has been planned.

While one direction of research is to increase the output power of the single-polarized output, the other direction is to design the fiber laser with dual-wavelength and single-polarization output. Dual-wavelength fiber lasers also have many interesting applications, such as differential frequency generation (DFG) for mid-infrared wavelength which is critical for pollutant chemical detections. In [7], the laser output with two orthogonally polarized wavelengths is realized by matching the wavelengths of two PM-FBGs. Though this technique delivers a narrow linewidth of 0.01 nm and high PER of 25 dB, the maximum wavelength separation is no more than 0.35 nm, limited by the birefringence of the PM-fiber. In addition, the adjustment of a polarization controller is required to match the wavelengths of FBGs in order to achieve the dual wavelength operation.

In [8], a dual-wavelength operation is achieved with a maximum tunable separation of 83 nm by using two bulk gratings and half wave-plates. An output with a 0.05 nm line width and 20 dB PER were obtained. In [9], a dual wavelength operation with 13 nm separation is obtained in an all-fiber structure by applying compression and tension to the two FBGs used simultaneously with a cantilever beam and translation stage. All the lasers in [7]–[9] operate in the 1-μm or 1.5-μm band. In [10], a dual wavelength laser operating at 1 μm and 1.5 μm simultaneously is reported using Er/Yb co-doped fiber. The laser output is single-polarized with 0.1-nm bandwidth but the output power is limited to 60 mW. The adjustment of bulk optic components is needed to realize the dual wavelength operation.

The above review clearly shows that it is still a challenge to design a stable dual-wavelength all-fiber laser with wide wavelength spacing and single-polarized output. In this paper, we present a compact, stable dual-wavelength all-fiber laser simultaneously lasing at 1-μm and 1.5-μm wavelengths. The laser is built around a PM Er/Yb co-doped active fiber with two PM-FBGs pairs at both 1057 nm and 1554 nm. A total output power of 1.3 W is obtained. The laser takes advantage of specially designed PM-FBGs, to achieve a linearly polarized output with a PER of 23 dB and a narrow bandwidth of 26 pm. The proposed fiber laser is a novel demonstration of a dual-wavelength fiber-based source, with a fundamental wavelength interval as far as about 500 nm in an all-fiber configuration.

2. Experimental Details

The schematic diagram of the fiber laser, with all fiber connections fusion spliced, is shown in Fig. 1. An 8.5-W diode laser at 975 nm with a multimode fiber output was used as a pump source. A PM single-mode Er/Yb co-doped double-cladding fiber of 2 m in length, with a mode field diameter of

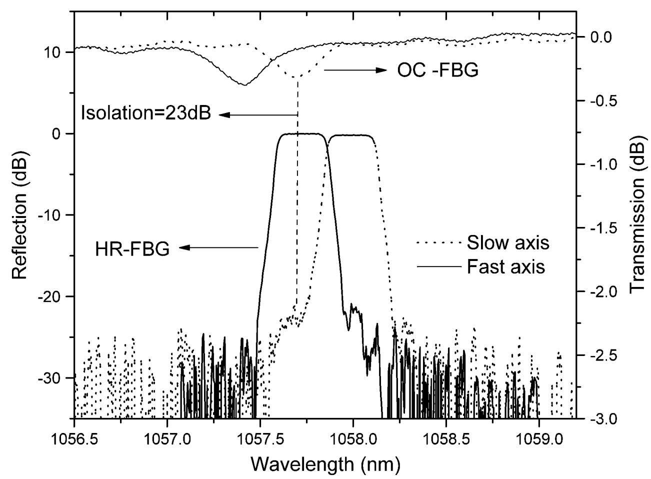

Fig. 2. Fiber Bragg Grating spectra at 1057 nm show the matching fast- and slow-axis wavelengths.

6.7 μm and an NA of 0.18, was used as an active fiber (Nufern: PM-EYDF-6/125). This fiber has an Er doping concentration of $N_{Er} = 2.42819 \times 10^{25}$ m^3 and Yb doping concentration of $N_{Yb} = 3.37 \times 10^{26}$ m^3 respectively (data from the manufacturer). The laser diode was spliced to a low pass filter which passed only the pump wavelength and blocked the longer wavelength ASE or spontaneously lasing that could burn the laser diode. Although the filter introduces $\sim$7% loss to the pump power, its use is necessary to protect the pump diode from damage.

To achieve wavelength and polarization selections, two FBG pairs were fabricated at 1057 nm and 1554 nm respectively, on a PM double-clad fiber with a core diameter of 5 μm and an NA of 0.12, (Nufern: 1060-GDF-5/130). For both wavelengths, FBG pairs were designed such that the slow-axis wavelength of the OC matched the fast-axis wavelength of the corresponding HR FBGs within 30 pm. FBG pair spectra designed at 1057 nm are shown in Fig. 2 with a flat-top and almost rectangular shape for HR FBGs. A similar design was used for the 1554-nm FBG pair (not shown). The fast- and slow-axis FBGs are separated by 0.26 nm due to the birefringence of the fiber.

The two FBGs spliced between the laser diode and the active fiber had high reflectivity of $>$ 99% and fast-axis wavelengths at 1554.3 nm and 1057.7 nm respectively. The HR-FBGs had an almost rectangular shaped spectrum with 23-dB isolation between its two polarizations. This high isolation is a key factor to realize a laser output with high PER. Both HR-FBGs were co-spliced to the active fiber, where both PM fibers had their fast axes aligned parallel to each other. The other end of the active fiber was spliced consecutively to two FBGs as OCs with reflectivity of about 10%. The OC-FBGs were cross-spliced to the active fiber, where their slow axes were aligned perpendicular to the slow axis of the active fiber as shown in Fig. 1. The fiber cavity thus designed selects both wavelength and polarization state. The details of the cavity design on single-polarization selection can be found in [4] and [5].

The pigtail of the OC was spliced to an angle-polished connector to prevent reflections from the fiber end. The laser output power was measured using a laser power meter with an integrated sphere (Thorlabs, Model S145C). A polarizing cube beam splitter (Thorlabs with an extinction ratio of 1000 : 1) was used to measure the PER.

3. Results and Discussions

The laser output parameters, such as output power, linewidth, PER and temperature tunability are presented as follows. The output power as a function of the diode pump power is shown in Fig. 3. Since two laser wavelengths emitted from the fiber are collinear, they need to be spatially separated for power measurement. A bulk grating of 180 lines/mm was used which separated the laser beams of 1554 nm and 1057 nm by $\sim$5 degrees. The laser output has a maximum output power of 0.67 W

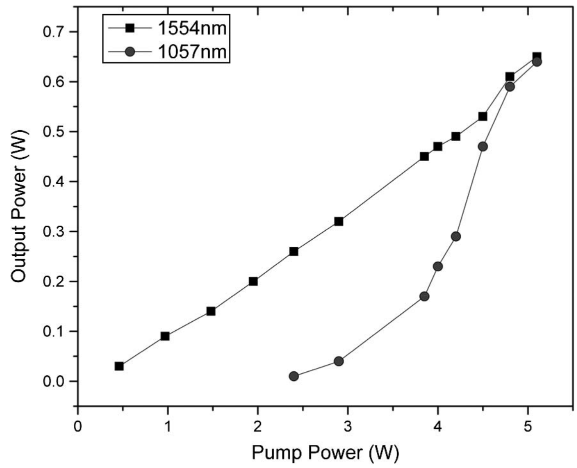

Fig. 3. Output power versus pump power for both wavelengths of 1554 nm and 1057 nm.

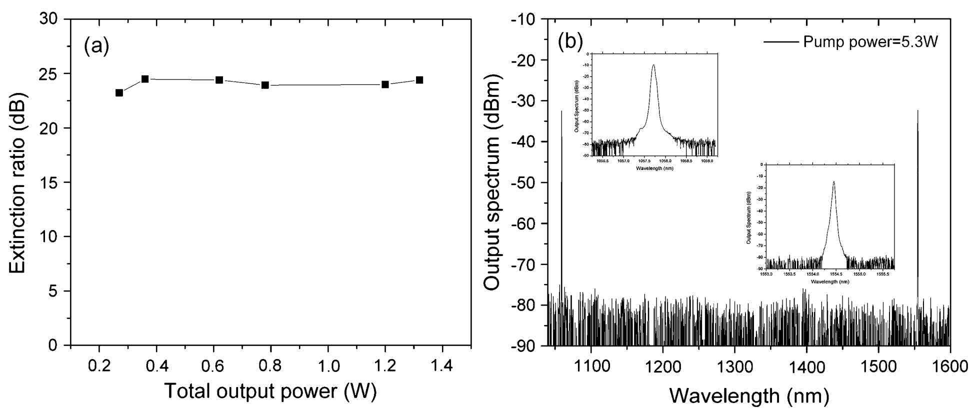

Fig. 4. (a) Extinction ratio in dB as a function of the laser total output power. (b) Laser output spectrum at 5.3 W pump powers. Insets show the details of the output spectra at 1057 nm and 1554 nm respectively.

and 0.65 W for both 1554 nm and 1057-nm wavelengths respectively at 5.3-W pumping power. It can be seen from Fig. 3 that 1057-nm laser power increases rapidly with pump power with a threshold almost 2.5 times higher than that of the 1554 nm emission. This can be explained as following: the active fiber is optimized so that erbium ions are primarily pumped via energy transfer from ytterbium, so only wavelength of 1554 nm lases at low pumping power. At a higher pumping level, a larger number of Yb ions are excited until a level is reached, at which 1057 nm wavelength starts lasing [10]. Above this level, the energy transfer between Yb and Er ions will be less efficient and 1057 nm output power will increase rapidly with increasing pump power. Since the active fiber is optimized for C-band operation, the 1057 nm cavity was made as an inner cavity to reduce its cavity loss and better match the power of 1554-nm laser output.

To measure the PER, the laser output pigtail was mounted on a rotating stage and collimated into a parallel beam by a lens. Then the laser polarization was aligned in the horizontal direction and transmitted through a polarization cubic beam splitter. The power of the transmitted beam and the reflected beam were measured when the laser output pigtail was rotated to maximize the power difference. The PER of 200 : 1 or 23 dB was obtained from the ratio of the two power readings. This high extinction ratio can be attributed to the high isolation between the slow and the fast axis wavelengths of the FBG. Fig. 4(a) clearly shows that a high extinction ratio was achieved over the

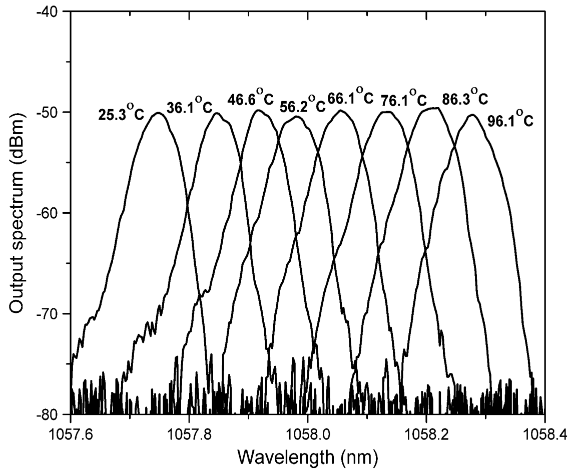

Fig. 5. Output spectrum of 1057 nm emission tuned by varying 1057-nm FBG pair temperature.

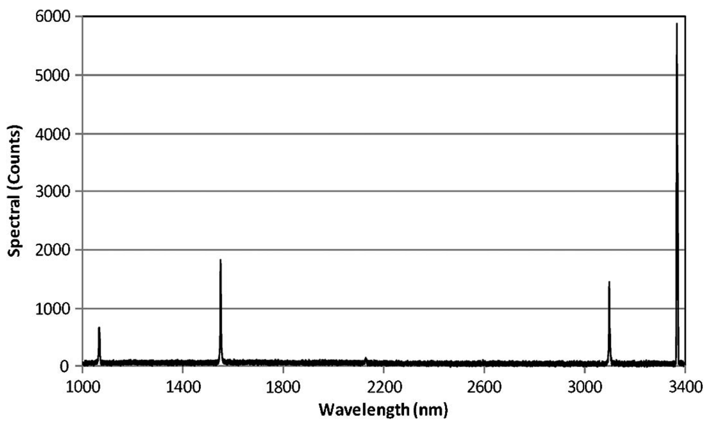

Fig. 6. Mid-IR spectrum from the PPLN crystal generated by the dual wavelength fiber laser.

whole power range. The stability of the output power was measured over 60 minutes; the power variation of less than ±2.0% was found at 1.3 W.

A narrow linewidth of the laser output is essential for efficient second harmonic or mid-IR generation using non-linear crystals or periodically poled $MgO{:}LiNbO_3$ (PPLN). The output spectrum of the dual-wavelength emission was measured with an optical spectrum analyzer (ANDO model: AQ6317), and the laser emissions at both 1057.7 nm and 1554.3 nm are depicted in Fig. 4(b). Both laser emissions achieved a narrow bandwidth of 26 pm at full-width half-maximum (FWHM) with an optical SNR of over 60 dB by separately measuring each band as shown in the inset of Fig. 4(b). To characterize the tuning capability of the dual-wavelength laser as a pumping source for mid-IR generation, the output wavelength was tuned by varying the temperature of the 1057-nm FBG pair. As shown in Fig. 5, the output wavelength can be tuned over a 0.6 nm bandwidth by varying the temperature from 25.3 °C to 96.1 °C.

The proposed dual-wavelength fiber laser was implemented successfully as a compact tunable pumping source for 3.3-μm mid-IR generation. The laser beam was focused into a 40-mm long 0.5-mm thick z-cut MgO:PPLN crystal with a period of 30.5 μm by a 25 $\times$ objective lens. The crystal was placed in a temperature-controlled oven, which in turn, was positioned on a multi-dimensional stage. The generated mid-IR emission was filtered by a double-coated Germanium window to remove the residual fundamental lights in near-IR. Fig. 6 shows the generated mid-IR emission of

0.23 mW at 3371 nm, in which, the residual pump wavelengths at 1057 nm and 1554 nm can still be seen. The peak at 3109 nm is the second order diffraction of the 1554.3 nm laser line that our mid-IR spectrometer did not block adequately. For a 40 mm long device used in our experiments, the FWHM bandwidth of the conversion efficiency for the generated mid-IR light at 3.37 μm is 16.9 nm if 1057 nm pump is tuned while the 1554 nm pump is fixed. The peak conversion efficiency is about 0.18% based on the measured intensities of the pump and generated mid-IR light. By tuning the temperature of the 1057 nm FBG pair from 26.5 to 106.5 °C, the wavelength of the mid-IR emission could be continuously tuned by ~6 nm, which is sufficient to cover several vibration-rotational absorption lines of methane.

4. Conclusion

In conclusion, we have demonstrated an all-fiber, dual-wavelength laser with a 500 nm separation and a 0.65 W output power at each wavelength. The cavity design used PM fibers for both gain medium and FBG cavity. The laser achieved a linearly polarized output with a high extinction ratio of 23 dB using the specially designed FBG pairs. The laser emission has an excellent SNR of over 60 dB and a narrow bandwidth of 26 pm at 1057 nm and 1554 nm respectively. Further improvement for output power can be accomplished by optimizing cavity design parameters. As demonstrated, this design is well-suited for a compact fiber-based DFG pumping source for mid-IR generation. The dual-wavelength emissions from the same laser cavity and gain fiber offer more stable output and smaller foot print as compared to other methods. This work shows that our special PM FBG cavity design can be used not only for scaling-up the power of a linearly polarized laser, but also for multi-wavelength linearly-polarized laser emissions.

References

[1] C. H. Liu, A. Galvanauskas, V. Khitrov, B. Samson, U. Manyam, K. Tankala, D. Machewirch, and S. Heinemann, "High-power single-polarization and single-transverse-mode fiber laser with an all-fiber cavity and fiber-grating stabilized spectrum," *Opt. Lett.*, vol. 31, no. 1, pp. 17–19, Jan. 2006.

[2] M. J. Li, D. A. Nolan, G. E. Berkey, X. Chen, J. Koh, D. T. Walton, J. Wang, W. A. Wood, and L. A. Zenteno, "High performance single polarization optical fibers," in *Proc. SPIE*, 2005, vol. 5623, pp. 612–621.

[3] D. Xue, A. R. El-Damak, and X. Gu, "All-fiber single polarized Yb-doped fiber laser with a high extinction ratio," *Opt. Commun.*, vol. 283, no. 6, pp. 1059–1061, 2010.

[4] A. Shirakawa, M. Kamijo, J. Ota, K.-i. Ueda, K. Mizuuchi, H. Furuya, and K. Yamamoto, "Characteristics of linearly polarized Yb-doped fiber laser in an all-fiber configuration," *IEEE Photon. Technol. Lett.*, vol. 19, no. 20, pp. 1664–1666, Oct. 2007.

[5] J. Wang, L. Zhang, J. Hu, L. Si, J. Chen, X. Gu, and Y. Feng, "Efficient linearly polarized ytterbium-doped fiber laser at 1120 nm," *Appl. Opt.*, vol. 51, no. 17, pp. 3801–3803, Jun. 2012.

[6] J. Wang, J. Hu, X. Lei Zhang, J. Gu, and Y. Chen, "A 100 W all-fiber linearly-polarized Yb-doped single-mode fiber laser at 1120 nm," *Opt. Exp.*, vol. 20, no. 27, pp. 28 373–28 378, Dec. 2012.

[7] P. Liu, F. Yan, C. Wang, F. Zhang, and C. Liu, "A switchable dual-wavelength all-fiber laser based on Panda-type photosensitive polarization-maintaining erbium-doped fiber," *Microw. Opt. Technol. Lett.*, vol. 52, no. 2, pp. 386–389, Feb. 2010.

[8] D. F. Liu and C. H. Wang, "Single linearly polarized, widely and freely tunable two wavelengths Yb^{3+}-doped fiber laser," *Opt. Commun.*, vol. 283, no. 1, pp. 98–103, Jan. 2010.

[9] R. Kim, S. Chu, and Y.-G. Han, "Stable and widely tunable single-longitudinal-mode dual-wavelength erbium-doped fiber laser for optical beat frequency generation," *IEEE Photon. Technol. Lett.*, vol. 24, no. 6, pp. 521–523, Mar. 2012.

[10] J. Boullet, L. Lavoute, A. Desfarges-Berthelemot, V. Kermène, P. Roy, V. Couderc, B. Dussardier, and A. Jurdyc, "Tunable red-light source by frequency mixing from dual band Er/Yb co-doped fiber laser," *Opt. Exp.*, vol. 14, no. 9, pp. 3936–3941, May 2006.